

UV CONTINUUM SPECTROSCOPY OF A $6L_*$ $Z = 5.5$ STARBURST GALAXY^{1,2,3}

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ABSTRACT

We have obtained a high S/N (22.3 hr integration) UV continuum VLT FORS2 spectrum of an extremely bright ($z_{850} = 24.3$) $z = 5.515 \pm 0.003$ starforming galaxy (BD38) in the field of the $z = 1.24$ cluster RDCS 1252.9-2927. From *HST* Advanced Camera for Surveys imaging this object was selected as a potential $z \sim 6$ Lyman break galaxy (LBG) based on its red $i_{775} - z_{850} = 1.5$ color. This object shows substantial continuum ($0.41 \pm 0.02 \mu\text{Jy}$ at $\lambda 1300$) and low-ionization interstellar absorption features typical of LBGs at lower redshift ($z \sim 3$); this is the highest redshift LBG confirmed via metal absorption spectral features. The equivalent widths of the absorption features are similar to $z \sim 3$ strong Ly α absorbers. No noticeable Ly α emission was detected ($F \leq 1.4 \times 10^{-18} \text{ ergs cm}^{-2} \text{ s}^{-1}$, 3σ). This object is at most amplified 0.3 mag from gravitational lensing by the foreground cluster. The half-light radius of this object is 1.6 kpc ($0''.25$) and the star formation rate derived from the rest-frame UV luminosity is $SFR_{UV} = 38 h_{0.7}^{-2} M_{\odot} \text{ yr}^{-1}$ ($142 h_{0.7}^{-2} M_{\odot} \text{ yr}^{-1}$ corrected for dust extinction). In terms of recent determinations of the $z \sim 6$ UV luminosity function, this object appears to be $6L_*$. The *Spitzer* IRAC fluxes for this object are 23.3 and 23.2 AB mag (corrected for 0.3 mag of cluster lensing) in the 3.6μ and 4.5μ channels, respectively, implying a mass of $1-6 \times 10^{10} M_{\odot}$ from population synthesis models. This galaxy is brighter than any confirmed $z \sim 6$ *i*-dropout to date in the z_{850} band, and both the 3.6μ and 4.5μ channels, and is the most massive starbursting galaxy known at $z > 5$.

Subject headings: galaxies: high-redshift — galaxies: individual (BD38) — galaxies: starburst

1. INTRODUCTION

Despite the large samples of photometrically selected $z \sim 6$ Lyman Break Galaxies (LBGs) (Bouwens et al. 2003, 2005), spectroscopic confirmation has been difficult, because of the faint flux levels required. Ground based follow-up programs have had success rates of $\sim 25\%$ by identifying redshifts through Ly α emis-

sion (Stanway et al. 2004a,b; Dow-Hygelund et al. 2005). Malhotra et al. (2005) have verified 23 $z \sim 6$ i_{775} dropout galaxies via the presence of strong Lyman continuum breaks using low resolution ACS Grism observations. However, none of these very low resolution spectra can be used to identify the absorption features necessary to measure metal abundances and to characterize the interstellar medium. To do this we need to observe anomalously bright objects to obtain high continuum S/N. The best example of this remains the strongly gravitationally lensed ($30\times$) $z \sim 3$ galaxy MS 1512-cB58 (Pettini et al. 2000).

In this Letter, we report on the spectroscopic confirmation of a particularly bright $z_{850} = 24.3$ Bouwens et al. (2003) $z \sim 6$ *i*-dropout candidate: object 1252-5224-4599, hereafter BD38, in the RDCS 1252.9-2927 field (CL1252) (Rosati et al. 1998). We show that this large ($r_{hl} = 0''.29$) starbursting galaxy has a Lyman continuum break and interstellar absorption features at a redshift of $z = 5.515$, but lacks Ly α emission. Throughout we adopt $(\Omega_{tot}, \Omega_M, \Omega_{\Lambda}) = (1.0, 0.3, 0.7)$ and $H_o = 70 \text{ km s}^{-1} \text{ Mpc}^{-1}$. All magnitudes are given in the AB system (Oke & Gunn 1983).

2. OBSERVATIONS, REDUCTION, AND ANALYSIS

The *Hubble Space Telescope* Advanced Camera for Surveys (ACS) observations of BD38 ($\alpha_{2000} = 12^h 52^m 56^s.888$, $\delta_{2000} = -29^\circ 25' 55''.50$) involved three orbits of F775W (i_{775}) and five orbits of F850LP (z_{850}). VLT ISAAC (6.0 hr for *Js* and 5.7 hr for *Ks*) and *Spitzer* IRAC (1000 s for both 3.6μ and 4.5μ) imaging were also obtained. For details see Bouwens et al. (2003), Lidman et al. (2004), and Fazio et al. (2004).

We measured the $i_{775} - z_{850}$ color magnitudes in $0''.6$

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apertures, and the total z_{850} magnitude was measured in a $1''.1$ aperture. For measuring the $z_{850} - Js$ and $z_{850} - Ks$ colors, we smoothed the z_{850} image to match the Js - and Ks -band psf, and used $1''.0$ apertures. The difference between the $1''.1$ and $0''.6$ z_{850} magnitudes was then added to the i_{775} , Js , and Ks magnitudes.

Using the z_{850} image as a model for the IRAC data, every object in the z_{850} image within $20''$ of BD38 was smoothed with a kernel to match the ACS and IRAC data. The normalization of this kernel was varied individually for every object until the χ^2 between the model image and the IRAC data was minimized.

The resulting ACS, ISAAC and IRAC images are shown in Figure 1. BD38's observed magnitudes are $i_{775} = 25.76 \pm 0.15$, $z_{850} = 24.25 \pm 0.05$, $Js = 24.1 \pm 0.1$, $Ks = 23.8 \pm 0.1$, $3.6\mu = 23.0 \pm 0.3$, and $4.5\mu = 22.9 \pm 0.4$. Clearly evident is the strong $i_{775} - z_{850}$ flux decrement. Furthermore, the object is increasing in luminosity towards longer wavelengths. Assuming the rest-frame UV continuum of BD38 satisfies the form $f_\lambda \propto \lambda^\beta$ we are able to derive a spectral slope of $\beta = -1.5 \pm 0.2$ over rest frame $\lambda 1400 - \lambda 3000$, from the z_{850} , Js , and Ks fluxes.

We spectroscopically observed BD38 using the Focal Reducer/low dispersion Spectrograph 2 (FORS2) on the 8.2-m VLT YEPUN Unit Telescope. We used the 600z grism with the OG590 blocking filter, yielding a resolution of 1.64 \AA per pixel. The slit width was $1''.0$. A total of 80 exposures were taken to acquire a 22.3 hr integrated spectrum. BD38 and three other i -dropouts were targeted serendipitously as part of a larger fundamental plane study. For details see van der Wel et al. (2005).

The 22.3 hr integrated FORS2 absorption spectra are shown in Figure 1. A precipitous continuum break is clearly seen at $\approx 7900 \text{ \AA}$, reducing the continuum from 0.41 ± 0.02 to $0 \pm 0.02 \mu\text{Jy}$. Six clear absorption features are indicated in the figure.

The continuum break is due to the $\text{Ly}\alpha$ forest, while the absorption features are the low-ionization interstellar (LIS) lines typically seen in LBGs at $z \sim 3$ (Shapley et al. 2003), and the UV spectra of local starbursts (e.g., Heckman et al. 1998). In Figure 2 we show BD38's spectrum along with the composite spectrum of 198 $z \sim 3$ LBGs that lack $\text{Ly}\alpha$ emission (Shapley et al. 2003), and object 2 ($z = 4.687$ LBG) of Ando et al. (2004). There is a strong similarity in each spectrum's continuum break and absorption features. This demonstrates that BD38 is a LBG at $z = 5.515 \pm 0.003$.

There appears to be some weak emission at $7920 \pm 1 \text{ \AA}$ which would be the expected position of the $\text{Ly}\alpha$ emission line. However, the S/N for this feature is poor. We determine a 3σ upper limit of $1.4 \times 10^{-18} \text{ ergs cm}^{-2} \text{ s}^{-1}$ on this features. This is an order of magnitude smaller than is seen for $z \sim 6$ LBGs with strong $\text{Ly}\alpha$ emission (Stanway et al. 2004b; Dow-Hygelund et al. 2005).

3. A $\sim 6L_*$ STARBURST GALAXY

3.1. Luminosity

BD38 is 1.3 mag (z_{850}) brighter than any other i -dropout found in its host field CL1252 (Bouwens et al. 2003), and is 0.4 mag brighter than any other verified $z \sim 6$ LBG to date (Bunker et al. 2003; Malhotra et al. 2005; Dow-Hygelund et al. 2005). Two common explanations for anomalously bright galaxies are (1) they are powered by an AGN or (2) they are gravitationally lensed. We

TABLE 1
STRONG BD38 INTERSTELLAR ABSORPTION FEATURES

λ_{lab}^a (\AA)	Ion	λ_{obs}^b (\AA)	z_{ion}^b	W_o^c (\AA)	$W_{o,z\sim 3}^d$ (\AA)
1260.42	Si II	8205.77	5.510	3.18 ± 0.15	1.85 ± 0.16
1302.17	O I	8485.38	5.516	3.05 ± 0.10	3.24 ± 0.16
1304.37	Si II	8498.43	5.515	-	-
1334.53	C II	8699.72	5.518	2.88 ± 0.13	2.34 ± 0.16
1393.76	Si IV	9079.21	5.514	1.92 ± 0.25	1.83 ± 0.23
1402.77	Si IV	9140.84	5.516	1.14 ± 0.07	1.01 ± 0.17
mean			5.515		

NOTE. — For ion O I, W_o and $W_{o,z\sim 3}$ contain O I $\lambda 1302.17$ + Si II $\lambda 1304.37$.

^aVacuum wavelengths

^bObserved wavelengths (heliocentric)

^cRest frame equivalent width and 1σ error

^dRest frame equivalent width for group 1 (G1) of the Shapley et al. (2003) $z \sim 3$ LBG sample

consider each hypothesis in turn.

The AGN interpretation of the high luminosity is unlikely. First, $\text{Ly}\alpha$ $\lambda 1215.67$ emission and N V $\lambda 1240$ emission, typical of AGNs (Osterbrock 1989), were not detected. Second, BD38 was undetected in Chandra and XMM Newton CL1252 surveys, with upper luminosity limits of $L_x = 1.6 \times 10^{43} \text{ ergs s}^{-1}$ and $6.5 \times 10^{43} \text{ ergs s}^{-1}$ in the 0.5-2 keV and 2-7 keV bands, respectively (Rosati et al. 2004). This excludes BD38 being a type-1 AGN (QSO), and the absence of high ionization spectral lines is inconsistent with this object being a low luminosity type-2 AGN. Finally, the object is very extended, lacks a point source, and has LIS features similar to lower redshift starburst spectra.

Gravitational amplification can only account for a small portion of BD38's high luminosity. BD38 is $88''$ from the CL1252 cluster center, and using the results of Lombardi et al. (2005) we estimate the gravitational magnification due to the cluster potential to be at most $1.3\times$ or 0.3 mag . Lensing by any obvious nearby galaxy has been calculated to be less than 3%. Therefore, we believe BD38 to be intrinsically very luminous.

BD38 is an extremely luminous ($z_{850} = 24.6 \text{ mag}$ de-lensed) galaxy for this epoch. If no evolution is assumed in the UV luminosity function from $z \sim 3$ to $z \sim 6$ for L_* , BD38 is a $4L_*$ object. However, using the observed evolution in L_* , this object is an even more extreme $6L_*$ (Bouwens et al. 2005). The surface density of such objects is estimated to be only one per 400 arcmin^2 . In fact, only one similarly bright (SBM03#3; $z_{850} = 24.7$) i -dropout has been found over the entire 320 arcmin^2 ACS footprint of the two GOODS fields (Bunker et al. 2003). Furthermore, BD38 is brighter than all the i -dropout objects discovered in the 767 arcmin^2 Subaru Deep Field (Shimasaku et al. 2005). In addition, BD38's $3.6\mu = 23.3$ and $4.5\mu = 23.2 \text{ mag}$ fluxes (de-lensed) are the largest found in any i -dropout object to date (Eyles et al. 2005), and are 0.6 mag brighter than SBM03#3 in the 3.6μ channel.

The UV magnitudes imply an $\lambda 1500$ continuum luminosity of $2.7 \times 10^{29} h_{0.7}^{-2} \text{ ergs s}^{-1} \text{ Hz}^{-1}$. This yields a star formation rate (SFR_{UV}) of $38 h_{0.7}^{-2} M_\odot \text{ yr}^{-1}$ (Madau et al. 1998). The $\beta = -1.5$ suggests that BD38 suffers from dust obscuration, and utilizing Eqs (11) of

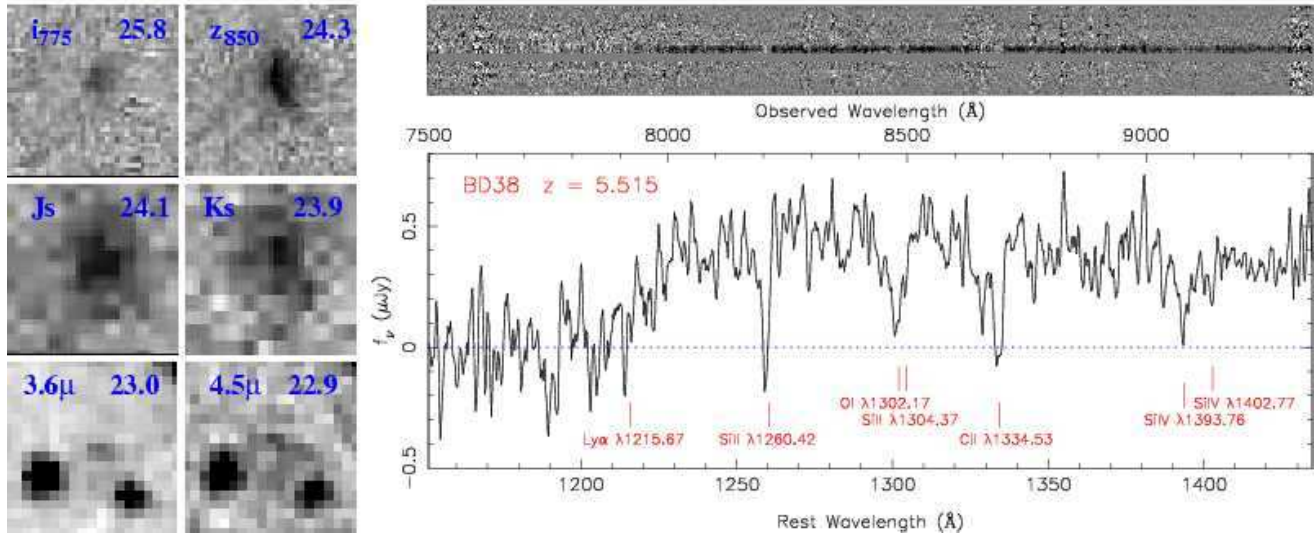


FIG. 1.— (Left) ACS, ISAAC, and IRAC imaging of BD38. The i_{775} , z_{850} , J_s , K_s thumbnails are $1''.5$ on a side. The 3.6μ and 4.5μ thumbnails are $15''.0$ on a side. The disturbed morphology of BD38 is apparent and, together with the spectroscopic data, suggests vigorous star formation. Furthermore, the relatively red z - J_s and z - K_s colors coupled with the strong LIS lines (see below), suggests BD38 is a relatively dust enriched and chemically evolved galaxy. The object is extended towards the lower-right (north-west) direction by $\approx 0''.26$ and by $0''.22$ upward (east). These “plumes” could be the product of a recent merger. (Right) Two- and extracted one-dimensional FORS2 spectra of BD38. The total integrated time was 22.3 hr. The gray smooth rectangular region of the two-dimensional spectrum covers a cluster member spectrum that occupied the slit. The one-dimensional spectrum has been smoothed with a 5 pixel boxcar filter. Strong LIS absorption features are marked, and the blue dotted line denotes zero flux. The equivalent widths of these lines are very similar to those found by Shapley et al. (2003) for 198 $z \sim 3$ LBGs that are strong Ly α absorbers (see Table 1). Utilizing these features yields a systematic redshift of $z = 5.515 \pm 0.003$.

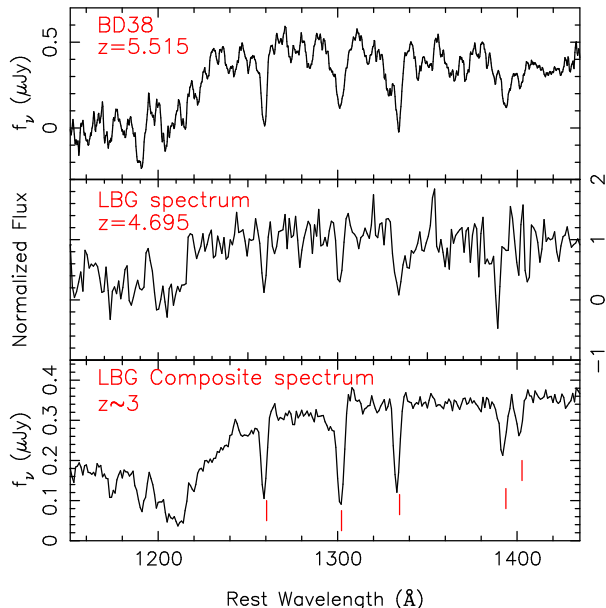


FIG. 2.— Spectral comparison between BD38, a $z = 4.695$ LBG spectrum from Ando et al. (2004), and Shapley et al. (2003) $z \sim 3$ composite LBG spectrum. BD38’s spectrum has been smoothed with a 13 pixel boxcar filter. The continuum break and marked absorption features show a strong match with BD38 and the LBG spectra, indicating this object is a starbursting LBG.

Meurer et al. (1999) yields a UV dust extinction value $A_{1600} = 1.45$ magnitudes. This increases SFR_{UV} by a factor of 3.78 to $142 h_{0.7}^{-2} M_{\odot} \text{ yr}^{-1}$.

3.2. Morphology and Color

BD38 has a delensed half-light radius of $r_{hl} = 0''.25$ (z_{850}), implying a physical half light radius of $r_{hl} = 1.6 h_{0.7}$ kpc. This object is among the largest i -dropouts at $z \sim 6$. This r_{hl} corresponds to the size of Luminous Blue Compact Galaxies in the local universe (Koo et al. 1994), though the SFR of BD38 is a factor of $\approx 6\times$ higher.

Though BD38 is unusually bright, its A_{1600} , SFR_{UV} , and r_{hl} resemble $z \sim 3$ LBGs and compact ultra-violet luminous galaxies (UVLGs) populating the local universe (Heckman et al. 2005). Averaging the equivalent width values of SiII(1260), OI(1302)/SiII(1304), and CII(1335) yields -3.0 \AA , similar to -2.5 \AA for G1 and -2.8 \AA for seven $z \sim 5$ LBGs (Ando et al. 2004), and those found for UVLGs. These lines are saturated, therefore they are not useful for measuring metal abundances (see Shapley et al. 2003). However, this similarity in the LIS equivalent widths suggests BD38’s combination of neutral gas covering fraction and velocity dispersion is similar to lower redshift starbursts.

3.3. Population Synthesis Modeling

Using the z_{850} , J_s , K_s , and *Spitzer* IRAC 3.6μ and 4.5μ data, we fit Bruzual & Charlot (2003) stellar synthesis models to BD38 using a similar methodology as Papovich et al. (2001) and Eyles et al. (2005). We use the dust models from Calzetti et al. (2000), and assume metallicities of 0.4 or $1.0 Z_{\odot}$.

We examined three sets of models for the spectral energy distribution (SED) of BD38: a (1) simple stellar population (SSP), a (2) constant, or (3) exponentially declining star formation. All models are poorly con-

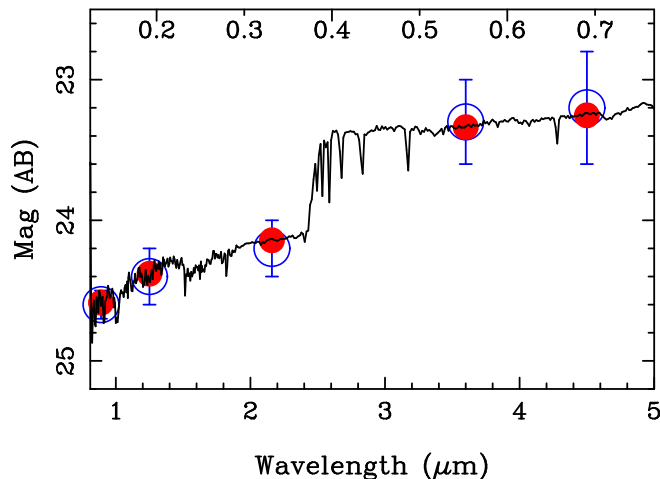


FIG. 3.— The best-fit Bruzual & Charlot (2003) SED for BD38. The open circles with error bars denote the measured magnitudes and the closed red circles represent the model SED magnitudes in each bandpass and channel. The upper and lower axes are the rest-frame and observed wavelengths, respectively. Model parameters are $\tau = 100$ Myrs, Z_{\odot} , age = 227^{+27}_{-35} Myr, $E(B-V) = 0.10^{+0.10}_{-0.10}$, and a mass = $43 \pm 13 \times 10^9 M_{\odot}$. The magnitudes have been dimmed by 0.3 mag to account for weak lensing by the cluster potential (§3.1). The clear rest $0.4 \mu\text{m}$ Balmer break suggests a dominant stellar population of at least 100 Myr.

strained because of having only five independent photometric measurements and the large errors on the IRAC fluxes. The best fitting SSP (minimum mass and age model) is a $0.4 Z_{\odot}$, $6.0^{+2.6}_{-0.4}$ Myr population with $E(B-V) = 0.26^{+0.04}_{-0.04}$ and a mass of $7.0 \pm 2.1 \times 10^9 M_{\odot}$. Assuming a constant star formation rate, yields a Z_{\odot} , 720^{+470}_{-300} Myr population with $E(B-V) = 0.13^{+0.07}_{-0.05}$ and a mass of $64 \pm 20 \times 10^9 M_{\odot}$. The lowest χ^2 model is an exponentially decaying star formation rate with $\tau = 100$ Myrs, a Z_{\odot} , 227^{+27}_{-35} Myr population with $E(B-V) = 0.10^{+0.10}_{-0.10}$ and a mass of $43 \pm 13 \times 10^9 M_{\odot}$. All errors are formal 68% confidence limits for the input model. We emphasize

that all of these models have competitive χ^2 values and that there are as many parameters (τ , Z , age, $E(B-V)$, and mass) as there are data points. It is striking that the most reasonable models (i.e., those with ongoing star formation) all imply large masses, with mass-to-light ratios typical of $z \approx 3$ galaxies (e.g. Labbé et al. 2005).

Using the same assumptions as Eyles et al. (2005), BD38 is at least 2-3 times more massive than the comparably bright ($z_{850} = 24.7$) $z = 5.78$ galaxy SBM03#03, though the stellar ages derived are similar. Hence, BD38 is likely the most massive $z \sim 6$ *i*-dropout LBG to date. Interestingly, SBM03#03 possesses strong Ly α emission, is compact (both unlike BD38), and is 0.6 mag fainter in the 3.6μ channel than BD38.

This object is unique, representing the tip of the $z \sim 6$ mass function. BD38 is likely a dusty ($E(B-V) \sim 0.1$), massive LBG composed of a large current burst of star formation ($SFR_{UV} = 40 - 142 h_{0.7}^{-2} M_{\odot} \text{ yr}^{-1}$) together with a slightly older population (6-700 Myr) of $1-6 \times 10^{10} M_{\odot}$ stars. These results are dependent upon the very shallow IRAC imaging; much longer integration times are necessary to confirm this interpretation. Mid-IR imaging would give much stronger constraints on possible SEDs.

Though this is only one object, its similarities with other luminous $z \sim 3$ LBGs give insights into evolution over the interval $3 \leq z \leq 6$. This object has (1) no noticeable Ly α emission, and (2) is more dust reddened than typical $z \sim 6$ objects (Stanway et al. 2005; Bouwens et al. 2005). These traits are typical of the more luminous high SFR_{UV} $z \sim 3$ LBGs (Shapley et al. 2003). Therefore, even though the universe was only half as old at $z = 5.5$ (1 Gyr) than at $z \sim 3$ (2 Gyr), the composition and star forming properties of extremely luminous objects appear to be essentially unchanged.

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